A CAPABLE AND TEMPORARY TEST FACILITY ON A SHOESTRING BUDGET: THE MSL TOUCHDOWN TEST FACILITY

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ABSTRACT

The Mars Science Laboratory mission (MSL) has undertaken a developmental Touchdown Test Program that utilizes a full-scale rover vehicle and an overhead winch system to replicate the skycrane landing event. Landing surfaces consisting of flat and sloped granular media, planar, rigid surfaces, and various combinations of rocks and slopes were studied. Information gathered from these tests was vital for validating the rover analytical model, validating certain design or system behavior assumptions, and for exploring events and phenomenon that are either very difficult or too costly to model in a credible way. This paper describes this test program, with a focus on the creation of test facility, daily test operations, and some of the challenges faced and lessons learned along the way.

KEY WORDS: Mars Science Laboratory, planetary landing, rover, skycrane, system testing

INTRODUCTION

The Mars Science Laboratory project will use the innovative Skycrane maneuver to land the rover on the surface of Mars in 2010. The MSL implementation of skycrane will require that the rover wheels and mobility system serve also as the landing system, without the use of airbags or other cushioning devices. In addition to the extensive analysis program for the touchdown event (Peng et al 2007), the MSL mission has undertaken a developmental Touchdown Test Program. This test program is a crucial link between the conservative assumptions and idealizations used for analysis and vehicle loads prediction, and realistic vehicle behavior during touchdown on sloped, granular media and in the presence of rocks. Information gathered from these tests will be vital for validating the rover analytical model, validating certain design or system behavior assumptions, and for exploring events and phenomenon that are either very difficult or too costly to model in a credible way.

The need for a Touchdown Test Program was envisioned by the MSL project from the very start, when the Skycrane approach was adopted. Original plans called for an ambitious permanent facility capable of testing a wide variety of landing events, not only the MSL Skycrane. As the project evolved, it became clear that a much less expensive approach for testing the landing event was needed. Plans for the permanent landing facility were cancelled, and this team received the mandate of creating the best possible test facility, and the best test program, on the smallest budget possible. Additionally, whatever was created for this developmental test program had to be available during the summer months of 2008 for the project's V&V testing.

A driving requirement for the facility was the need to support a load of 5000 lbs at a minimum height of 13m. Few facilities at JPL qualify with enough height; the logical choice was the Static Test Tower, Building 280. This facility is a popular one, so an additional requirement was that our facility would have to be temporary, able to be disassembled in a matter of a week or two, stored over the winter, and re-assembled again quickly for V&V testing.

Touchdown testing was the main focus of the program, but a suite of interesting tests was also performed on the rover. All of these tests (except Mass Properties) were performed using the touchdown test facility:

- Mass Properties using three-point support. Total mass and CG were measured by supporting the rover from below in a level configuration and a 30° inclined configuration. This test was carried out on the Rover Assembly Cart.
- Stiffness Testing. System-level rover vertical and lateral stiffness were determined using static loads.
- Strain Gage Calibration. An extensive program of vertical and lateral loads on the mobility system allowed for precise gage calibration. Explained in detail below.
- Simple Wheel Drop tests.

This paper explains the most interesting aspects of the design, construction, and operation of this facility. The discussion starts with a description of the test article – the developmental rover nicknamed SCARECROW.

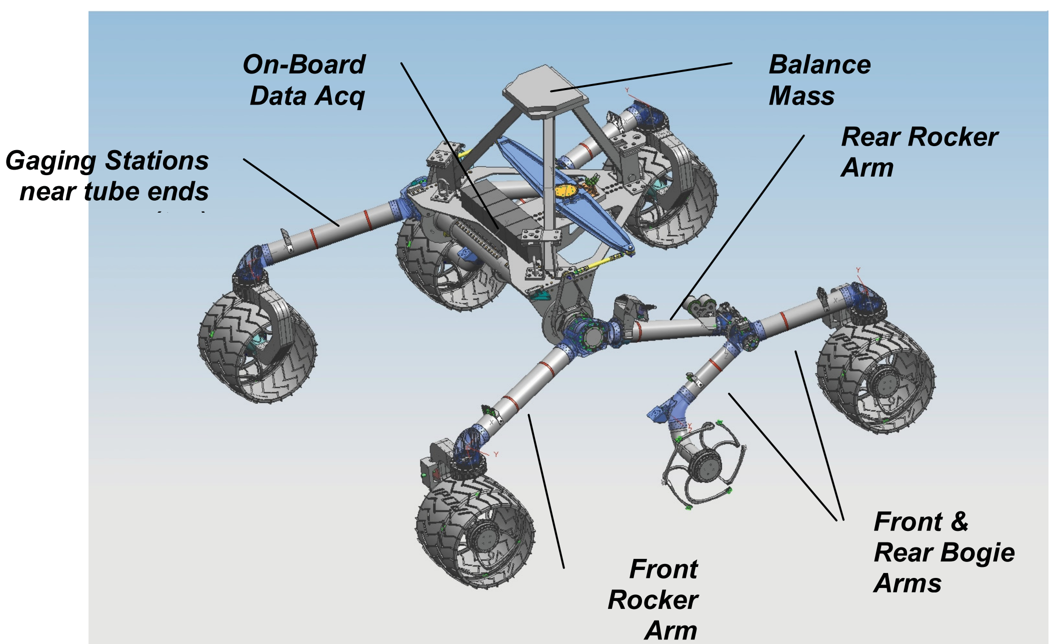

Figure 1 The MSL SCARECROW Rover (wheel removed to show detail). The vehicle has a 289kg mass and a footprint of approximately 2.75m wide and 2.75m long.

ROVER VEHICLE & ON-BOARD INSTRUMENTATION

The SCARECROW rover shown in Figure 1 is a full geometric scale and 3/8th mass scale vehicle, comprised of the chassis and mobility subsystems. The mobility subsystem is a rocker-bogie design built to the flight design as it existed after the Preliminary Design Review, with no mass scaling. The chassis is designed to maintain the structural integrity of the vehicle, and to provide the proper vehicle mass and CG location, hence the large balance mass. The mobility subsystem is comprised of thin-walled aluminum tubes riv-bonded to end fittings at the joints. Bogie pivots provide independent rotational motion of the bogies while the rockers pivot through the differential system at the rocker-chassis interface, and at the central differential pivot on the chassis top deck. The flexibility of the mobility subsystem is divided among the structural flexibility of the suspension tubes, and the special titanium wheel flexures between the hubs and the tires. Drive motion is provided by actuators located in the hubs of all six wheels, with steering accomplished by independent steer actuators at the four corner wheels of the vehicle.

Forces and accelerations at touchdown are acquired through an on-board rover data acquisition system. The system uses a COTS system from UEI – the Data Cube. The Data Cube is housed inside a custom box that also includes signal conditioning boards. Data is relayed to a host computer within the facility through a single Ethernet cable. The system is powered by a 12V supply brought out to the rover through the data umbilical. Total mass of the system is 10.5 kg. The sensor suite includes rotational pots at the joints, a system of 4 triaxial 25g accelerometers (0-100 Hz), a system of 4 triaxial 2g accelerometers (0-50 Hz), a rotational rate gyroscope, three load cells at the bridle attach points, and a system of 52 strain gages, for a total channel count of 84 channels. Sample rate was set at 1000 samples/sec. The innovative Anderson Loop wiring technique (Anderson 1997) was used on the strain gages to minimize wire count and parasitic stiffness across the rotational joints.

Ensuring the accuracy of the strain gage system required in-situ calibration tests on the fully assembled SCARECROW. The approach used carefully controlled load application points to effectively isolate each suspension tube to the extent possible, and apply static loads to activate particular internal forces. Vehicle system stiffness data was also measured by simply measuring deflections at key locations.

Horizontal calibration loads were achieved by squeezing the suspension arms together at certain points using an adapted 6-to-1-advantage sailing block and tackle and manually pulling the rope end. The wheels were replaced with special ball transfer feet during testing to eliminate friction and precisely define the support contact points. Lateral deflection was measured at several points on the mobility system with precision string pots, and from this data lateral stiffness of the system was computed. Vertical calibration loads were applied by pulling downward on the chassis underside, immediately below the two side chassis-mobility interface points. The downwards load was achieved using a length of UHMW polyethylene rope run through a pair of floor-mounted pulleys and up to a 10,000 lb capacity Hydraset device attached to the overhead winch rope. Precision scales measured the increase in vehicle reaction load, so that the load going into each suspension tube was known with high accuracy. Effective isolation of the rear rocker required supporting the bogie pivots with special stands and repeating the chassis loading.

Another special test was used for calibrating the rear rocker torsion gages. Torsional loads were put into the rear rockers using the same sailing block-and-tackle system attached to two clamp-on torque arms, which converted the lateral load into a torsion load on the rocker. The torque arms were simple two-piece aluminum plates clamped onto the end of the rear rocker with a thin rubber strip sandwiched in the interface to provide friction but keep from marring the surface of the rocker arm. Although limited in the amount of torque that could be applied due to slipping at the interface, this system was highly effective.

TEST FACILITY DEVELOPMENT

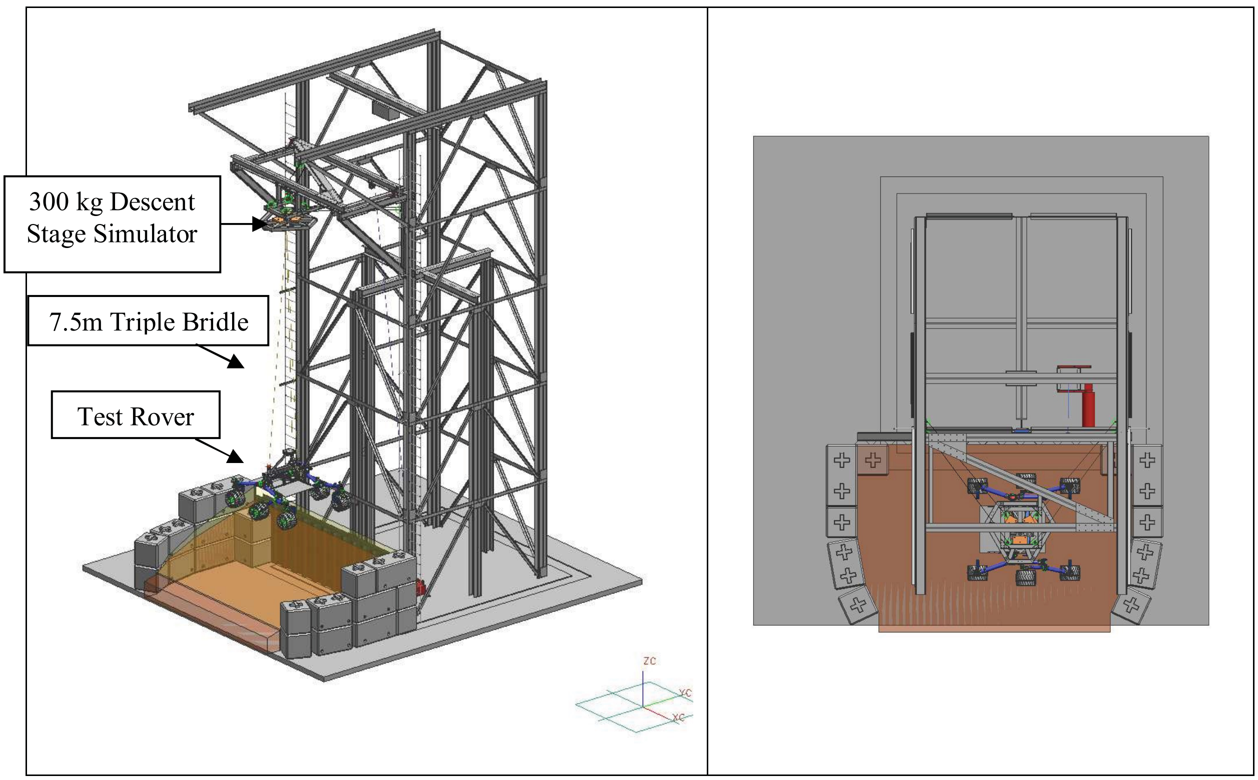

Figure 2 Schematic layout of the entire test facility. Note the 20HP winch motor (shown in red) located inside the static test tower.

Figure 3 Ready for action! A photo of the test facility upon completion of the winch system.

Building

The complete facility, ready for touchdown testing, is shown in Figure 2 & Figure 3. The building features a 50 ft tall steel tower structure with a 15 ft square plan. Ordinarily, spacecraft are placed inside the tower for static and modal testing. Many spacecraft, including Galileo, Cassini, and parts of Mars Exploration Rovers have been tested in this facility. The landing area was shoehorned into the building in front of the tower, between the South tower face and the 25foot tall rollup door of the building. A special knee-brace structure was outfitted near the top of the South columns of the tower and served as the means to support several overhead pulleys. A 5T overhead gantry crane was left parked inside the tower. Control of vertical descent of the rover was provided by a 20Hp electric winch.

The large size of the vehicle in relation to the facility is evident in the plan view in Figure 2. With the rover rotated 90 degrees to face down the slope, the clearance to the back wall is about 1.5 feet. It was necessary to provide for capability to land the vehicle in any heading, with any horizontal velocity direction. Pre-test simulations of the landing event indicated that for slopes of 30°, rover instability & escape was a distinct possibility, but for slopes up to 15°, the rover was not expected to buck or jolt out of the facility.

The as-built layout, which was close to spilling out of the building, had both pros and cons associated with it. The lack of extra space in the building meant there was no room for rover staging or storage. Instead, the rover had to be stored in an adjacent building and moved to the test facility. On the pro side, it made spectator viewing easy, it made it easy to access the landing area with a telescoping forklift, and it allowed sufficient sunlight into the building to permit high speed videography with minimal supplemental lighting.

Sandbox

Key requirements for the landing surface are summarized in Table 1. It was immediately apparent that some type of sand containment structure was needed. A huge advantage of creating a landing surface with a large pile of sand is that any angle can be achieved, and that a pile of sand is much less expensive than a large and stiff structural system. From the design standpoint, the key issue is the lateral pressure from the sand, which varies as the square of the depth of sand. An associated issue is the means to support seismic loads, which are enormous for such a volume of sand. Part-way through the project, landing requirements (and test requirements) were descoped from 30 degrees to 15 degrees. This descope proved critical to an economical solution.

Table 1 Initial Design Requirements for Sand Containment Structure

Item	*Requirement or Goal ?*	*Rationale*
Angle of Incline		
The ramp should provide inclines of 0 degrees and 15 degrees	Requirement	This scope was agreed to as a compromise between capability and cost
The ramp should provide infinite adjustability for all inclines up to 30 degrees.	Goal	To provide ability to investigate stability during touchdown event
Loads & Load Factors		
The ramp shall be designed to a factor of 1.5 on dead loads and 2.0 on live loads	Requirement	No JPL Critical Items are to be used in this facililty. Intended as a conservative design
The ramp shall be designed for all relevant dead loads plus a landing load of 16000N concentrated at a signle point	Requirement	
The ramp shall resist a seismic load of 0.45W	Requirement	JPL Facilities Design Standards
Stiffness		
The ramp should be stiff in the normal direction so that the normal deflection under maximum impact event is limited to 10% of the deflection of the test article suspension - Expressed as a specific deflection, the reqmnt shoud be [3 mm].	Requirement	To approximate the bounding condition of landing on a rigid surface
Terrain		
The ramp shall accommodate the following terrain types: Rigid planar (steel plate) w/out rocks , sand with rocks, sand without rocks	Requirement	Directly traceable to goals of test program
The ramp shall provide a minimum sand depth of 0.5m	Requirement	Experience with MER shows one wheel diameter is sufficient for minimizing reflection effects
The ramp shall provide a means for firmly supporting 0.5m rocks	Requirement	Directly traceable to goals of test program
The ramp should provide ability to mount rocks to the rigid planar	Goal	Completeness in terrain types

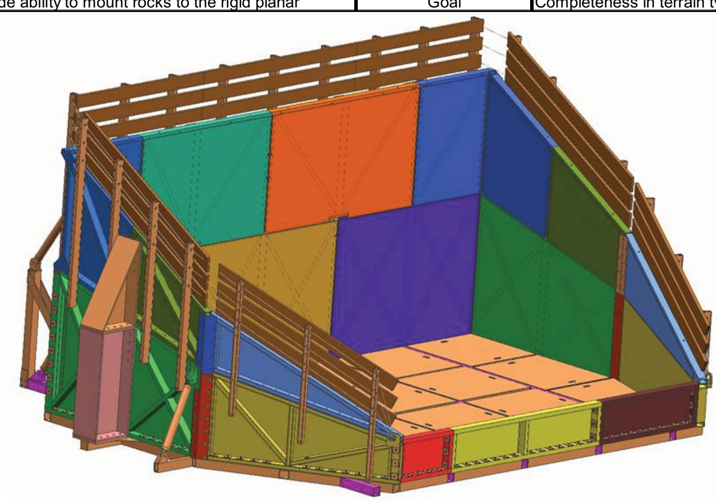

Figure 4 The first sand containment structure was a free-standing steel frame and panel system. A 30° slope capability is shown. The need for containment railings was eliminated when the maximum slope was lowered to 15°.

A sand containment structure was designed under subcontract to the Lab (Figure 4). This structure went out for fabrication bid and the resulting bids were significantly larger than the budget. Rather than pursue that structure, the JPL team came up with a configuration shown in Figure 5 that uses interlocking landscape blocks and sections of standard interlocking steel sheet piling and steel beams. The lateral sand pressure was resisted by the massive weight of the blocks; the failure mode was sliding under lateral pressure and seismic. A few angle clips bolted to the floor pushed that failure mode above the design load. Lateral pressures along the back wall were resisted by the sheet piles bearing, ultimately, on the columns of the tower. The lack of space prohibited using landscape blocks here. The total finished cost was on the order of 10% of the cost of the original sand containment structure.

Basaltic sand was purchased from a commercial mining operation in the Mojave Dessert. This sand had a favorable grain size distribution, and more importantly, the sand was clean and dry, having been passed through a kiln during processing. The sand produced enormous clouds of fine dust when it was unloaded or disturbed. To ensure personnel safety while working with the sand, the JPL Personnel Safety Office required the use of half-mask respirators for all personnel working with the sand, and established a personnel air sampling program for the first work session. The results of the air sampling program indicated very low exposure levels to personnel, so that respirators were not needed for subsequent operations. The only preventive measure we took during loading and unloading the sandbox was to cover all sensitive equipment in the building. Of course, every surface of the building received a thin coat of basaltic sand dust. One day of cleaning with compressed air at the end of the program was sufficient to clean the building.

The sand pile was transformed into a rigid landing surface by burying a network of 8x4x1/2" steel angles in the sand and bolting a 3/8" thick steel plate to the angles. This worked extremely well.

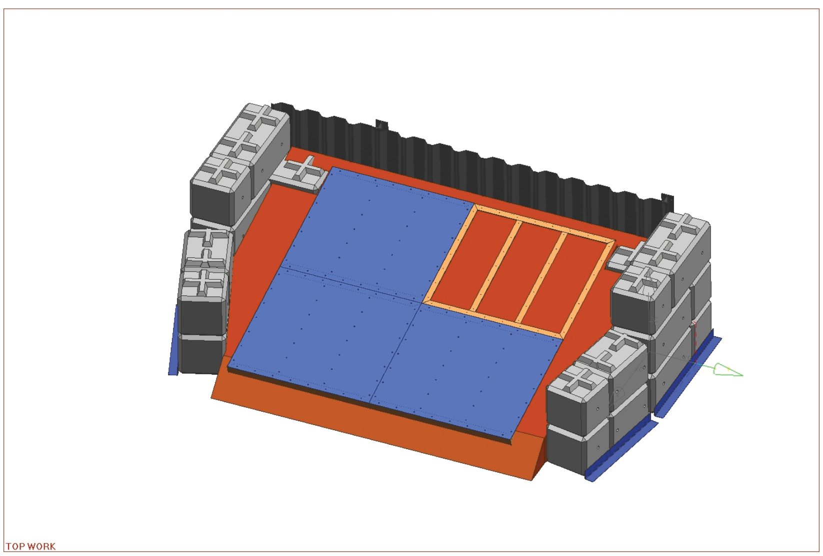

Figure 5 The as-built sand containment structure. Maximum slope capability is near 20°

Winch System

A 20 HP electric winch was used to raise and lower the rover at specified velocities. The system was integrated from standard commercial hardware with custom software and safety interlock systems developed by the JPL team. The block diagram below (Figure 6) provides some details of the winch system, and outlines its interfaces to the control and data acquisition systems.

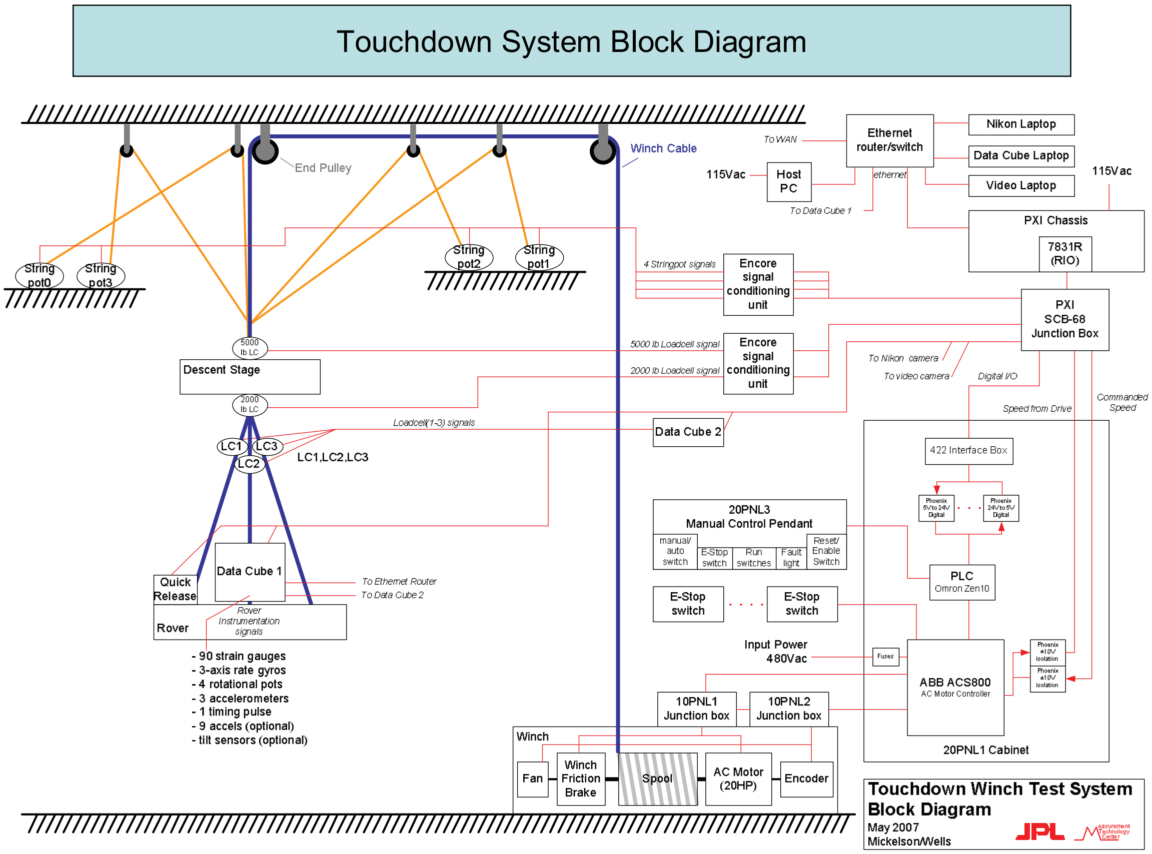

Figure 6 Schematic view of the winch control system and integrated data acquisition systems, and high-speed and still-camera imaging systems.

The safety and interlock system operates across the hardware and software boundaries and can be best described by its five layers.

Level 1: The *System Power Interlock* relies on the fail safe nature of the winch mechanical brake in that power is required to disengage the brake. Thus, if power is lost at any time, the brake will be set.

Level 2: *Hard Travel Limits*: The winch drum employs four micro switches which are used as upper and lower travel limits. The two upper limits (initial and final) are set to prevent the end of the winch rope from being pulled up into the pulley system. The two lower limits are set to prevent the system from reaching the ground, unless this is the planned operation. The only way to move the system out of a final limit position is by resetting the system, and by-passing the limit switches using a special fixture which must be placed into the system, and removed after the fault is cleared.

Level 3: These are the *Motor Controller Limit Levels*, acting on velocity limit, ramp-up and ramp-down times, and the brake application rules. In addition, pendant controls are sent to the motor controller via the PLC, while the e-stop controls are direct inputs to the motor controller.

Level 4: These are *Measurement-Based* protections which rely on the velocities and accelerations measured by an embedded real time measurement system which is implemented in an FPGA based RIO (re-configurable I/O) product from National Instruments (the PXI-7831R). This system calculates the velocity and acceleration of the payload by time-differentiating positions measured by string potentiometers. In the event of a limit exceedance, the digital I/O portion of the RIO provides a signal to the PLC and motor controller to protect the payload.

Level 5: *Winch Operator Intervention*. The winch operator is provided with a computer GUI interface which mimics the control pendant and operates as a dead man switch. If the operator does not hold the mouse button down during an automated descent, the test will terminate, and the brake will be set. The operator can also stop the test at any time using a stop switch on the GUI. And finally, the emergency stop buttons (of which there are three positioned around the facility) can be operated by observers at any time that an unusual event occurs.

One of the prime concerns the team had was how to verify the loop stability of the combined motor control, winch motor, rope, and payload while operating under all of the possible conditions. The motor controller uses a proprietary digital controller to 'linearize' the control function. Outside of this linearization function, there is a standard PID loop which can be tuned by the user. In our case, the proprietary loop made it difficult to analyze the system because of the limited insight into the transfer functions associated with the loop. The alternative, and what we selected, was to use a standard Zeigler-Nichols approach, which was somewhat risky due to the fact that we were lifting 1800 lbs as we searched for the stability limit of the PID loop! We were able to clearly demonstrate well over 6 dB margin on the gain, but the phase margin was never precisely determined. After returning the gain to the nominal value, we never saw any signs of instability during the test program, even when we tested simulated landings by suddenly off-loading 50 % of our test load.

Even before we could verify system stability, as described above, it was necessary to ensure that dozens of variables on the motor controller were properly set. A good example is found in the delays and pre-loads associated with braking. If not set properly, the load can drop between the time that the brake is released, but before the motor develops the torque needed to provide lift. While an elevator company would be well aware of this critical functionality, it might not always appear on the radar screen of a spacecraft engineer! In the end, our relationship with the ABB Motor Controller vendor proved to be a valuable one, which contributed to our success.

A key requirement on the software was to accommodate a user-provided descent profile that the rover would follow. Once the motor control, winch motor, rope, and bridle simulator dynamics were understood, a profile could be loaded into the RIO (real time FPGA) and a test could be run. However, the RIO compile time was a little too long to count on recompiling every time we needed to change the descent profile. The solution was to program a normalized profile into the FPGA, then program changes into the RIO via control registers without changing the FPGA code itself. This provided a near-real time update capability that allowed the user to specify scaling factors on a normalized profile. This saved a great deal of test time during the test campaign.

After a lengthy development and test period, the winch friction brake began to show some signs of wear. This was discovered during one of the proof-load tests when the proof load started to creep slowly. The brake mechanism on the winch motor is adjustable, but it was decided to verify our margins rather than make a change to the system part way though. The margins were verified through a bi-weekly proof test program.

FACILITY OPERATION

The main workhorse of daily operations was a Manitou 523 telescoping forklift. This vehicle, with a forward reach of nearly 10 feet and a lifting capacity of 5000 lbs, had a set of interchangeable front-end attachments including a lifting hook, forks, and a 1.25 cu yd bucket. With it we assembled the steel beams, sheet piling, and landscape blocks for the sandbox; we filled the sandbox with sand using the bucket attachment; we lifted and carried the rover; we placed the steel fame and landing platform, and we lifted and installed large rocks on the landing platform. Perhaps most important of all, the Manitou with the forks attachment was used on a daily basis for rigging the Descent Stage and rover into the test configuration, a process described below. Throughout our experience, the only shortcoming of the vehicle was that the horizontal reach was not quite long enough.

A second indispensable machine was a Manlift Snorkel with 50 foot reach. This allowed access to the top of the tower to service and maintain the pulleys and various other equipment. The alternative was to contract with an outside rigging company, a slow and less flexible alternative. This was our only choice at the start of the program.

A single touchdown test required many steps. A procedural checklist with 165 entries was followed for every test sequence. A central characteristic of the operations was to hook a 300 kg Descent Stage into the load path, 7.5m above the rover. The basic steps in this procedure were as follows:

- Lift rover onto landing surface and position in-line with winch rope
- Remove lifting sling from rover and install 7.5m bridles onto rover
- Remove lifting hook from Manitou and install forks
- Load Descent Stage (D/S) onto Manitou forks
- Bring D/S over adjacent to rover, and connect bridles to bottom of D/S
- Bring winch rope down and connect to top of D/S
- Establish electrical connections
- Using Manitou, carefully fork D/S above rover (about 12 feet off the ground)
- Using winch, lift D/S from Manitou forks
- Lower Manitou forks and drive Manitou backwards out of the area.
- Slowly lift D/S until bridles no longer slack, lift rover 1 foot

Upon completion of this operation, control was passed from the winch pendant to the computer-based automatic control system. The rover was raised the final few feet to 'Home' Position and the touchdown test was nearly ready. (The 'Home' configuration is illustrated in Figure 2.) From the time the D/S was brought in above the rover, there was no access to the rover. This made it difficult to inspect the rover up-close after a particular test. The maximum number of tests the crew accomplished in an 8-hour day was nine. Some days, we did only two drops. On a typical day, it would require about 2 hours of focused work to get the rover ready to lift 1 foot off the ground. A total of 85 touchdowns were performed, over a period of about six weeks.

The original budget estimates were for a winch operator, one full-time flight technician, and the test conductor. We miscalculated. Our crew consisted of four highly qualified flight techs, a winch operator, a test conductor, and a dedicated Safety Professional to oversee all operations and control onlooker crowds. Miscellaneous other jobs required a handful of other people: to run standard video cameras, to hold the portable diffuser, to hold tag lines, etc. Sometimes onlookers were pressed into service on these odd jobs. Onlookers were generally available. Several tests drew crowds of a few hundred people. In general, and especially early in the program, the presence of the larger crowds added stress to the crew that was not particularly welcome.

Obviously safety was a paramount consideration. Two features of this program had a large influence on safety considerations: the temporary nature of the facility, and the large risk to life safety presented by the overhead loads. It was necessary to strike a balance between providing built-in safety features through hardware and software functionality and achieving safety through operational procedures. The proper balance emerged through close cooperation with JPL Safety professionals. A thorough written Safety Plan was essential for providing visibility and allowing the safety features to be reviewed by peers. Peer reviews of the Safety Plan, the winch functionality, and the detailed operational procedures were extremely useful, as was daily participation and oversight from the Safety Office.

Safe operations also depend on a capable and well trained crew. Constancy in the test personnel was critical, so every attempt was made to keep substitution of crew members to an absolute minimum. After a day or two of test operations, the crew developed a real team attitude, and specific roles and responsibilities for each member became clear. Initially, some important tasks were handled by whichever crew member was available. As we are about to describe, this practice was flawed, and ultimately we fixed the roles and responsibilities of each crew member. Focused crew meetings were held every morning before operations began, and most afternoons. Constant communication and critical examination of our procedures allowed us to improve throughout the entire program.

The test program experienced one unfortunate incident when the winch rope jumped a pulley grove and jammed, suddenly stopping the rover's descent and leaving the rover hanging 5 ft off the ground. The post-mortem examination immediately showed that somehow, the pulley rope guard had been defeated, the rope had jumped the grove and gotten wedged between the side of the pulley and the pulley bracket. Examination of data signals, the video and crew interviews established that the most probable cause for the failure was associated with using improper procedures for recovering from a loose rope condition. The loose rope was accidentally generated during the daily winch inspection routine, but while winding the loose rope back onto the winch drum, the rope was mistakenly pulled taut in a lateral direction to the pulley grove, rather than parallel to the grove. As the rope was taken back up under power from the winch motor, the rope walked along the side of the pulley flange, slipped under the guard, and was riding on a flange on the side of the pulley. This condition went unnoticed by the test conductor for one complete touchdown test, and on the second test, the rope finally wedged itself with force into a narrow gap between the pulley side and the bracket. This tripped the winch safety interlock system, immediately stopping the test.

After the incident, it took about 6 hours to safely remove the rover and the descent stage. The descent stage was secured with slings to the overhead steel structure, providing a parallel load path to the damaged rope. Then very carefully the rover was hooked onto a forklift by the lifting slings, unhooked from the descent stage, and lowered to the ground. Finally, a chain lift was hooked onto the descent stage and lowered to the ground. The next day the damaged pulleys and rope were recovered for complete post-mortem inspection. A six-week hiatus from testing was needed while repairs were designed and fabricated. Pulley fairleads and improved guards were added, a higher quality pulley was used in one position, and a surveillance video camera was mounted at each pulley. Procedures were added to include inspection of the pulleys before each move of the load, and key data was post-processed, printed, and reviewed by the test conductor after every test.

This event strengthened the crew tremendously. Attentiveness became the watchword, and the message was reinforced everyday in the morning meetings. The slightest anomaly was noticed and brought up for discussion. Roles for every crew member were more rigidly fixed. The crew actually gained confidence. Complacency never developed, attentiveness and focus were the watchwords for everyone. The remaining six weeks and 75 touchdown tests went smoothly.

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BIOGRAPHIES

Dr. White is a senior engineer in the Mechanical Systems Engineering Division, Entry, Descent & Landing Group at JPL. His interests encompass dynamic performance of a wide variety of mechanical systems, from both analysis and test perspectives. Prior to this project, he was Telescope Structure Group Leader for the analysis and design of the 30m Telescope Project, Lead Mechanical Engineer for the analysis, design, and technology development of novel membrane telescope reflectors, Lead Structural Engineer for the analysis and technology development of balloons and blimps for planetary exploration, and involved in the analysis and test of the airbag landing system of the Mars Exploration Rovers. He holds A PhD in Civil Engineering from Cornell University, with a focus on active control systems.

Mr. Frankovich is a recent graduate of The University of Texas at Austin with a BS in Mechanical Engineering. He has been working in JPL's Mechanical Integration and Test group since 2006. His experience includes developing mechanical support equipment for various tasks on the Mars Science Laboratory Mission.

Mr. Yates is a Member of the Technical staff with the Measurement, Test, and Engineering Support Section at JPL. He has worked at JPL since 1991 in various areas including Metrology, Technical Management of the Measurement Technology Center, Technical Group Supervisor of the Measurement Systems Group. Project support for many projects, including the NSCAT, SeaWINDS, and QuickSCAT scatterometers, Cassini, Mars Pathfinder, Mars Exploration Rover, Primary Atomic Reference Clock in Space, Aquarius Flight Thermal Controls. Mr. Yates was trained in Metrology while a member of the USAF.

Mr. Wells was graduated from Cal Poly Pomona in 1969 with a B.S. in Electronics Engineering. Upon graduation, he joined the JPL Instrumentation Section. George has used LabVIEW to develop ground support software products for several JPL flight missions, including Galileo, BETSCE, Mars Pathfinder, SeaWinds, CloudSat, PARCS, Aquarius, and several tasks for the current Mars Science Laboratory Mission.

Mr. Losey is an instrumentation engineer in the Measurement Technology Center at JPL. He Came to work at the JPL Edwards AFB facility as an Instrumentation Technician in 1979, and received his BS in Computer Science from Chapman University in1984. Upon graduation, he accepted an engineering position and transferred to the JPL Facility in Pasadena. He started building NI LabVIEW systems in 1990, and since 2003 he has been a certified LabVIEW Developer.